THE DIURNAL VARIATION OF SUMMER RAINFALL AT DENVER

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At Denver, Colo., practically all of the precipitation that occurs during November, December, January, and February is in the form of snow. Rain has been recorded a few times during these months, but it was of short duration or soon turned to snow. During March, April, and October considerable rain occurs, but the precipitation is chiefly in the form of snow. During the remainder of the year, May to September, inclusive, precipitation is chiefly rain, although considerable snow has fallen in May and September. The tipping-bucket gage cannot be used to measure snowfall; and hourly amounts of precipitation, therefore, are not available from October to April, inclusive. For that reason the diurnal variation in amounts and frequency for summer rainfall only will be discussed in this paper. In the last 20 years 55 percent of the precipitation has occurred during these 5 months.

Data for the 20-year period, 1919 to 1938, inclusive were used. It is believed that this period is of sufficient length to smooth most of the abnormalities due to excessive rains for short intervals of time.

The average hourly distribution of rainfall is shown graphically in figure 1. The same data are given in table 1. An examination of these data shows that the largest amounts occur in the afternoon and early evening hours. This characteristic is especially pronounced in July and August. The amounts for the hours ending at 5 p. m. and 9 p. m. in May appear to be much at variance, but these abnormalities can be accounted for by the occurrence of thunderstorms with excessive rainfall. In 1931, 1.02 inches fell between 4 p. m. and 5 p. m. Likewise in 1938, 1.58 inches fell between 8 p. m. and 9 p. m. Both occasions were associated with thunderstorms, and both amounts were equal to one-third of the the total fall during the 20-year period for the respective hours.

All months show a decided decline in average amounts between 11 p. m. and 1 p. m. The greatest average precipitation is 0.26 inch for the hour from 4 p. m. to 5 p. m. in August. The least amount, a trace, also occurred in August between 11 a. m. and noon. The total fall during this hour for the 20-year period was only 0.05 inch.

The duration of rainfall was approximated by considering the hours during which rain fell without regard to the exact time of beginning and ending. Thus, all computations were in multiples of 1 hour, and those hours wherein a trace only was recorded were kept separately. The total hours during which a trace of rain was recorded are shown in figure 2. Figure 3 shows the total number of hours in which 0.01 inch or more was recorded. To check more accurately the time of rainfall the actual beginnings and endings were considered during July for the entire 20-year period. This method of computation gave a total time equal to approximately 70 percent of that given by the first method in the case of measurable rains, 0.01 or more, and about 40 percent for traces only. Since the distribution curve is approximately the same by both methods, no additional computations were made for the other months.

The periods of maximum frequency for traces only and for 0.01 or more occur in the afternoon and early evening. The frequency curves have the same general trend as the curves showing the average hourly amounts of rain. Compare figures 1, 2, and 3.

The hour of greatest frequency, measurable amounts considered, is 5 p. m. to 6 p. m. in August. If traces only are considered the greatest frequency is in the hour from 4 p. m. to 5 p. m. in July. When the total frequency is considered, the maximum is from 4 p. m. to 5 p. m. in August. The hour of minimum frequency is from 4 a. m. to 5 a. m. in July. In the 20 years under discussion measurable rain occurred just twice during this hour. In other words the chances of rain in this hour are 2 in 620. Using traces only, the hour of minimum frequency is the hour just preceding the time of minimum frequency for measurable amounts, or 3 a. m. to 4 a. m. in July. Three traces were recorded in this hour in 20 years. Frequency data are shown in table 2.

An examination of the frequency charts reveals many interesting things. While it is conceded that measurable rains are of chief concern in the matter of outdoor activities, transportation, etc., any discussion of rainfall frequency should include traces along with the measurable

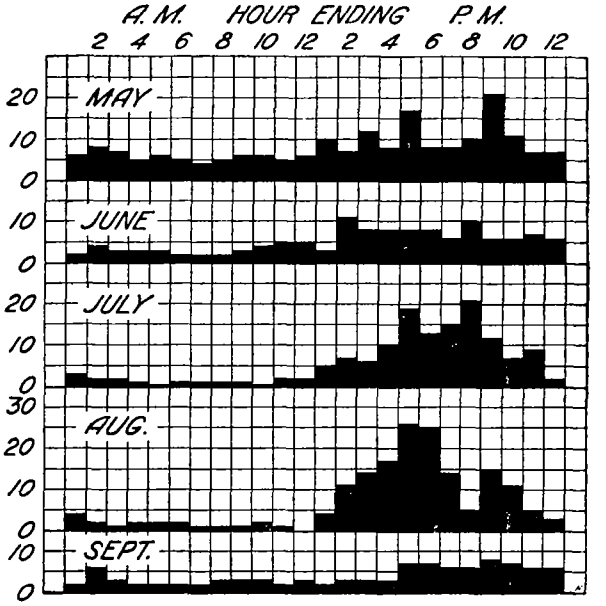

FIGURE 1.—Average hourly rainfall for 20 years, 1919 to 1938, inclusive. Amounts in hundredths of an inch.

amounts because often measurable amounts are simply the accumulated totals of preceding hours. Moreover, it has been found that traces at the official gage of the Weather Bureau are often accompanied by heavy showers nearby. This is shown very strikingly upon examination of the rainfall records of the city office, located in the heart of the business section of Denver, with those of the airport station, located about 5 miles east-northeast of the city office.

The outstanding feature of the frequency charts is the paucity of rain between 11 p. m. and 11 a. m. In order to show this better the actual number of times that rain occurred was plotted instead of the average for each hour. The average per hour for this period would be less than 1, traces only considered, in June, July, August, and September. The same holds true when measurable rains are considered, but is even more pronounced. There is a marked similarity in the trend of the curves for frequency and average hourly rainfall. Rainfall amounts during the night and forenoon are very small, which is to be expected in view of the low frequency of occurrence.

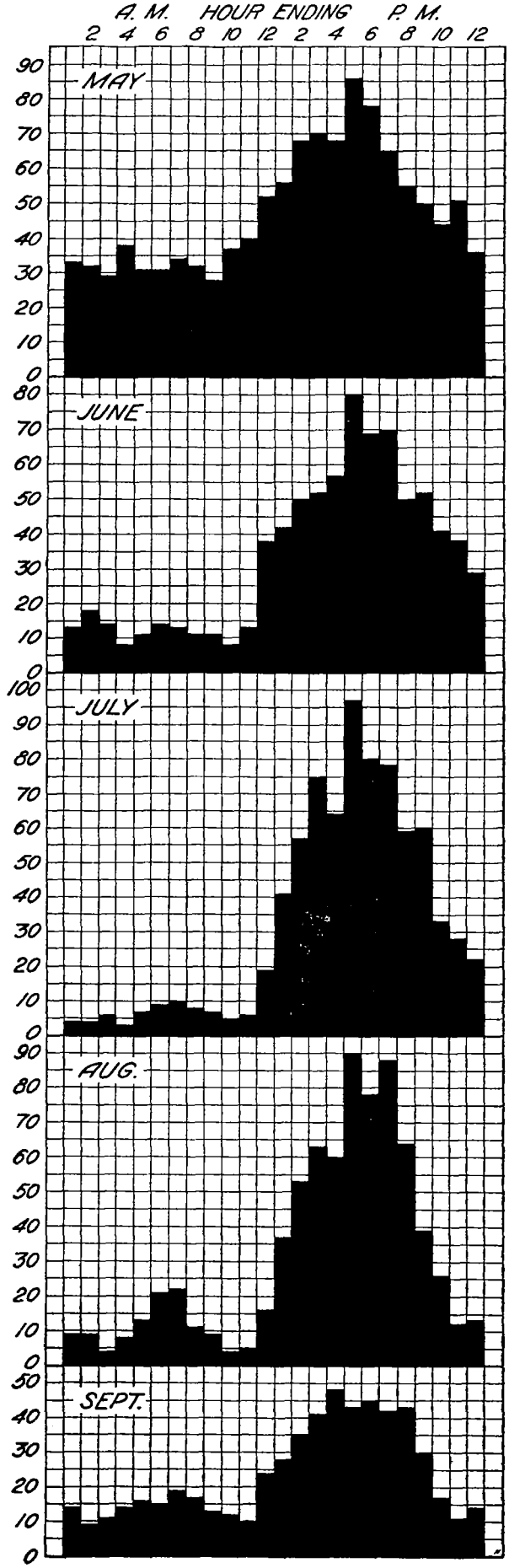

FIGURE 2.—Frequency of occurrence of a trace of precipitation. Figures indicate the total number of times that a trace occurred during each hour for the period 1919 to 1938, inclusive.

During the 20 years under consideration there were 1 May, 3 Junes, 10 Julys, 6 Augusts, and 5 Septembers when no measurable rain was recorded between midnight and noon. In the same 12-hour interval the total fall for the month exceeded 0.25 inch only 17 times in May, 5 times in June, 4 times in July, 4 times in August, and 7 times in September. If we divide the day into two 12-hour periods it is found that 62 percent of the summer rainfall occurs in the daytime interval or between 8 a. m. and 8 p. m. However, if we take the 8 hours of maximum rainfall, or from 1 p. m. to 9 p. m. we find that 47 percent

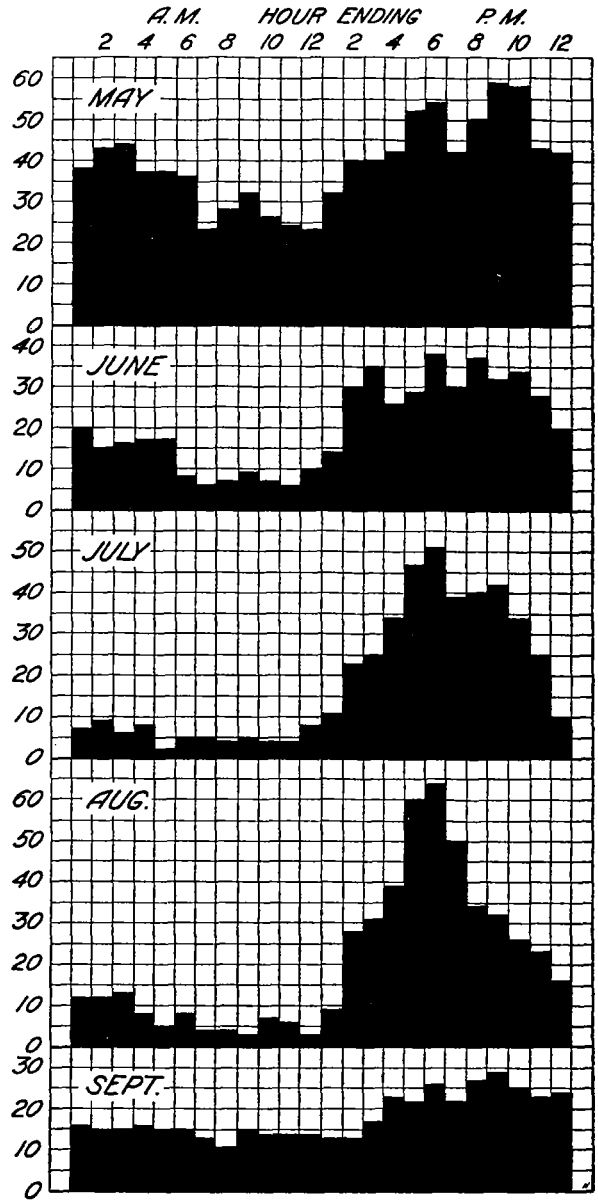

FIGURE 3.—Frequency of occurrence of 0.01 inch or more. Figures indicate the total number of times that 0.01 inch or more has occurred during each hour in the period 1919 to 1938, inclusive.

of the rain occurs in this period in May, 52 percent in June, 73 percent in July, 75 percent in August and 44 percent in September. The average for the entire 5 months is 51 percent.

Although rains of 1 inch per hour have been recorded during the period under discussion, they are not at all common. This will be seen from an examination of the data. During the 20 years covered in this study rains of 1 inch or more in 1 clock hour occurred twice in May, twice in July and three times in August. These numbers would be increased somewhat if rains of 1 inch or more per

hour were considered without reference to the clock hours. Considering the total fall for the day, it was found that surprisingly few days have had a total of 1 inch or more of rain. There were 5 days in May, 5 in June, 2 in July, 4 in August, and 3 in September, when the total fall for the day was in excess of 1 inch. This makes a total of only 17 days in 20 years when a rainfall of 1 inch or more was recorded. The chances of 1 inch of rain on any 1 day are small, indeed, or 17 in 3,060. This amounts to 1 day in 180 or less than 1 per summer.

The heaviest fall in any 1 hour was 1.72 inches for the hour 7 p. m. to 8 p. m. July 31, 1919; and the heaviest fall for any 1 day was 2.93 inches on August 23, 1921.

It seems that the greater amounts of precipitation in the afternoon is directly associated with the daily thunderstorm distribution. Thunderstorm activity is usually not very well marked in May until after the middle of the month, and this may be a contributing factor in the more evenly distributed hourly rainfall values. The reverse situation occurs in September. Thunderstorm frequency wanes rapidly after the middle of the month, and this also contributes to a more uniform variation in hourly rainfall.

A graph was prepared, figure 4, to show the diurnal distribution of thunderstorms. Only the hour during which the thunderstorm began was used, hence no thunderstorm is recorded in more than 1 hour. Thunderstorms at Denver are usually of short duration and it is not often that one lasts longer than 2 hours. Most are terminated within 1 hour after beginning.

The close resemblance in the curves of figure 4 to those for the corresponding months in figures 2 and 3 is most striking. The paucity of thunderstorms between 10 p. m. and noon and the high concentration in the afternoon seem to justify the statement that the rainfall distribution is closely associated with the diurnal variation of thunderstorms.

A further examination of the rainfall and thunderstorm data was made, and it was found that during May 44 percent of the precipitation fell in connection with thunderstorms. The percentages for June, July, August, and September are 75, 90, 87, and 37, respectively. In making this compilation all the rain on any day during which a thunderstorm occurred was used, whether it fell in connection with the thunderstorm or at some other time during the day. It is believed that there is justification for this, because if a thunderstorm occurred at any time during the day it would indicate that an unstable condition existed. Any rain falling during such an unstable condition would be of thundershower type.

At Denver the average number of thunderstorms in May is 8; in June, 13; in July, 14; in August, 15; and in September, 5. These storms are of such frequent occurrence at Denver, even more frequent in the neighboring mountains, that the public accepts them as commonplace. However, to the meteorologist they are of more than passing interest. Studies of the causes, indications, and forecasting of the thunderstorms have been made. While conclusive observational material is not available at the present time, the results of these preliminary studies seem to indicate that the thunderstorms are local in character and influenced chiefly by the physical features surrounding Denver.

Denver is situated in the Great Plains about 40 miles east of the main range of the Rockies, whose average altitude is in excess of 10,000 feet, and about 15 miles east of the foothills. About 40 miles south of Denver is an east-west connecting spur known as the Palmer Lake Divide. It has an altitude of about 7,300 feet. Denver is about 5,280 feet above sea level and located near the southwest corner of the "pocket" formed by the main range and the spur.

Except during periods of active cyclonic storms the nighttime wind at Denver is light and parallels the main mountain range. Under such conditions the wind may be classed as a drainage wind and is predominatnly from the south. The eastward face of the Rockies presents a surface nearly normal to the first rays of the summer sun. In response to the greater heating there than over the level plains there is soon a flow of air up the mountain side and the wind at Denver shifts rapidly after sunrise from southerly to easterly and finally to a northeasterly

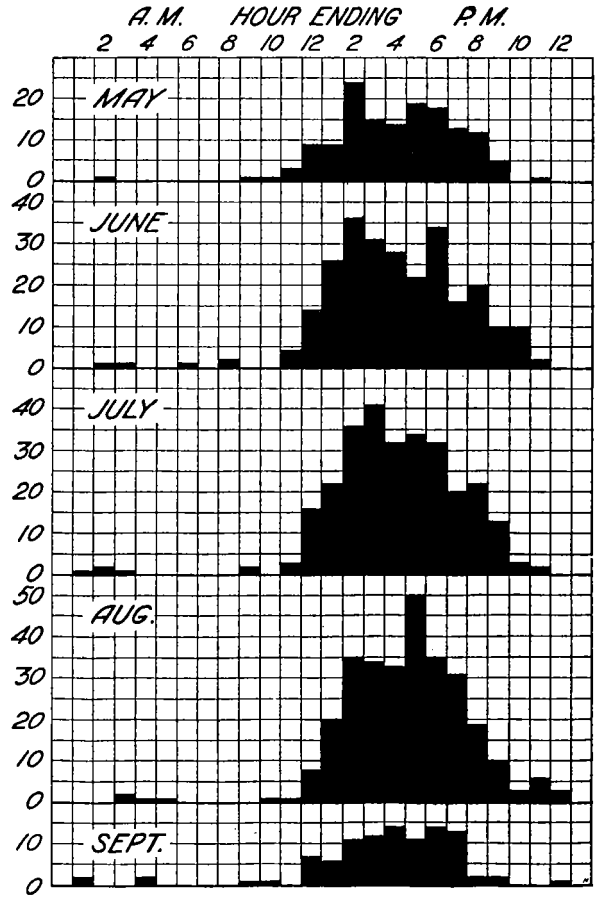

FIGURE 4.—Diurnal distribution of thunderstorms at Denver, Colo. The figures indicate the total number of storms for each hour, 1919 to 1938, inclusive.

direction. Despite the fact that Denver is nearly 40 miles from the mountains this shift in wind is pronounced and the easterly winds usually have velocities of 10 miles per hour or more. As the morning progresses, the flow of air toward the mountains becomes stronger; and if there is sufficient moisture in the atmosphere cumulus clouds soon begin to appear along the mountains southwest of Denver. The first cumuli are usually visible before 10 a. m. By noon the cumuli have grown into towering cumulo-nimbus clouds whose tops extend above the mountains. The fully developed thunderstorms then move out over the plains. However, they soon dissipate and it is not often that they are of any importance after they have traveled 75 miles from the point of origin.

One of these typical storms, on June 22, 1938, was studied in some detail. Rainfall records from cooperative stations were examined and it was found that 0.98 inch of rain fell at Bailey, about 30 miles south-southwest of

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Denver. The fall at Denver was 0.28 inch. Stations west of Denver and north of Bailey reported falls ranging from 0.05 to 0.35 inch. There was only a trace at Greeley, 40 miles north-northeast of Denver. No rain was recorded south of the Palmer Lake Divide and the only station east of Denver reporting rain was Byers, about 30 miles, air line, and the amount was only 0.02 inch. In this case the storm appeared to move almost due north of the place of formation, near Bailey, with rain along its path and east of the Rockies. The storm dissipated north of Fort Collins, or about 80 miles from its source. No rain was recorded north of Fort Collins, but the fall there was 0.30 inch. The time of occurrence of the thunderstorm at the cooperative stations is not known and for that reason the progress of the storm could not be checked.

Sometimes these thunderstorms form simultaneously at several places along the mountains. The direction of movement is northerly, northeasterly or easterly. Southerly or westerly movements have not been observed. This observation led to the supposition that the storms might be moving with the winds aloft over the mountains. A few cases were studied in which it was certain that the tops of the cumulo-nimbus were well above the height of the mountains, and in these cases the storm did move in the same general direction as the winds at 14,000 feet as shown by the winds-aloft report from the Denver airport. However, much more study on this phase of the problem is necessary before a positive statement can be made.

It is not intended to convey the impression that all thunderstorms at Denver are of this type. Frontal thunderstorms do occur, but it is recognized that the action along cold fronts in summer is not strong during the night because of the ground inversions that are so common. However, during the day thunderstorm activity along even weak fronts may be greatly accentuated. Furthermore, it is believed that many of the thunderstorms that occur after sunset are simply the aftermath of storms that were initiated during the day, but did not develop as rapidly as usual.

SUMMARY

In this paper statistical data covering amounts and frequency of rainfall at Denver during the 5 summer months, May to September, inclusive, for the 20 years 1919 to 1938, inclusive, are presented. These data show a high concentration of rainfall amounts and the highest frequencies in the afternoon and early evening with almost negligible amounts between midnight and noon, especially in June, July, and August. Thunderstorm data for the same period are presented and a close correlation between diurnal thunderstorm variation and daily rainfall variation exists. It is concluded that the thunderstorms are the prime factor in summer rainfall distribution at Denver.

The paper by Alexander [1] has an excellent bibliography on this subject, but to be complete the discussion of San Francisco rainfall by Counts [2] should be added to it.

[1] Alexander, H. F. A Study of the Hourly Precipitation at Oklahoma City, Okl., Monthly Weather Review, 1938, 66: 126–128.
[2] Counts, R. Corday, Jr. Hourly Frequency and Intensity of Rainfall at San Francisco, Calif. Monthly Weather Review, 1933, 61: 225–228.

TABLE 1.—*Average hourly distribution of precipitation at Denver, Colo., for the 20-year period, 1919–38, inclusive*

	Hour ending—																						
	A. M.											Noon	P. M.										Midnight
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
May	0.06	0.08	0.07	0.05	0.06	0.05	0.04	0.05	0.06	0.06	0.05	0.06	0.10	0.07	0.12	0.08	0.17	0.08	0.08	0.10	0.21	0.11	0.07	0.07
June	.02	.04	.03	.03	.03	.02	.02	.02	.03	.04	.05	.05	.03	.11	.08	.08	.08	.08	.06	.10	.06	.06	.07	.06
July	.03	.02	.02	.01	T	.01	.01	.01	.01	T	.02	.02	.05	.07	.06	.10	.19	.13	.15	.21	.12	.07	.09	.02
Aug	.04	.02	.01	.02	.02	.02	.01	.01	.01	.02	.01	T	.04	.11	.14	.17	.26	.25	.14	.05	.15	.11	.05	.03
Sept	.02	.06	.03	.02	.02	.02	.02	.03	.03	.03	.02	.03	.02	.03	.03	.03	.07	.07	.06	.06	.08	.07	.06	.06

TABLE 2.—*Total number of hours with rain at Denver, Colo., for the 20-year period, 1919–38, inclusive*

		Hour ending—																						
		A. M.											Noon	P. M.										Midnight
		1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
May	Traces	33	32	29	38	31	31	34	32	38	37	40	52	56	68	70	68	86	78	65	55	50	44	51	36
	0.01 or more	38	43	44	37	37	36	23	28	32	26	24	23	32	40	40	42	52	54	42	50	59	57	43	42
	Total	71	75	73	75	68	67	57	60	70	63	64	75	88	108	110	110	138	132	107	105	109	101	94	78
June	Traces	13	18	14	8	11	14	13	11	11	8	13	38	42	50	52	57	80	69	70	59	52	41	38	29
	0.01 or more	20	15	16	12	12	8	6	8	9	7	6	10	14	30	35	26	29	38	30	37	32	34	28	20
	Total	33	33	30	20	23	22	19	19	20	15	19	48	56	80	87	83	109	107	100	87	84	75	66	49
July	Traces	4	4	6	3	7	9	10	8	7	5	6	19	41	57	75	64	97	80	78	59	60	33	28	22
	0.01 or more	7	9	6	8	2	5	5	4	5	4	4	8	11	23	25	34	47	51	39	40	42	34	25	10
	Total	11	13	12	11	9	14	15	12	12	9	10	27	52	80	100	98	144	131	117	99	102	67	53	32
August	Traces	9	9	4	8	13	21	22	11	9	4	5	16	37	53	63	60	90	78	88	64	39	26	12	13
	0.01 or more	12	12	12	8	5	8	4	4	3	7	6	3	9	28	31	39	60	64	50	34	32	26	23	16
	Total	21	21	16	16	18	29	26	15	12	11	11	19	46	81	94	99	150	142	138	98	71	52	35	29
September	Traces	14	9	11	14	16	15	19	17	13	12	10	24	13	13	17	23	22	26	22	27	29	25	23	24
	0.01 or more	16	15	15	16	15	15	13	11	15	14	14	14	28	35	41	48	43	45	42	43	30	17	11	14
	Total	30	24	26	30	31	30	32	28	28	26	24	38	41	48	58	71	65	71	64	70	59	42	34	38